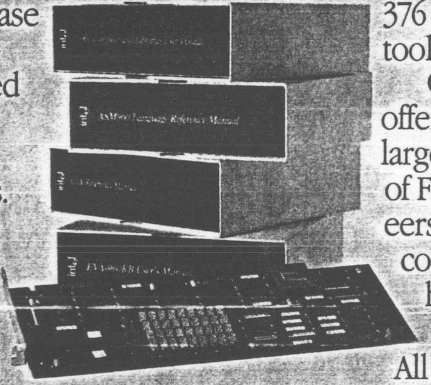

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CIRCLE NO 107

Clever techniques improve thermocouple measurements

Thermocouple (TC) measurements require linear-circuit proficiency. To ensure accurate results, you should understand the need to compensate for parasitic junctions, the importance of certain characteristics of the op amps and associated components, and the ways to otherwise condition and linearize the TC's low-level output signals.

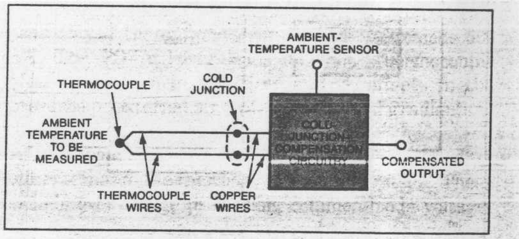


Fig 1—For accurate thermocouple measurements, *the thermocouple's cold junction and the compensation circuit's temperature sensor must be isothermal.*

Jim Williams, *Linear Technology Corp*

Thermocouples are inexpensive, but achieving reasonable accuracy—say ±0.5°C—requires careful signal conditioning and cold-junction compensation. Although thermocouples don't require any external excitation, and their small size and low output impedance produces wideband, low-noise output signals, their nonlinear, millivolt-level outputs degrade measurement sensitivity.

A TC senses ambient temperature by producing, across the junction, a small voltage proportional to temperature. To measure that voltage, you must connect the TC wires to an amplifier or voltmeter, creating two unwanted parasitic junctions that produce error voltages in series with the desired signal (**Fig 1**). These parasitic junctions must have the same temperature. To interpret the TC voltage as an absolute-temperature signal, you must either maintain these parasitic junctions at a known temperature or compensate for their effect electronically. The TC, in effect, measures temperature at its "hot" junction with respect to temperature at the two parasitic junctions—historically called the "cold junction."

Cold junctions generate spurious voltage

The term "cold junction" derives from the practice of maintaining the parasitic junctions at 0°C by immersing them in a mixture of ice and water. Although very accurate, this approach is impractical for most applications. As another option, you can simulate the ice bath by servo-controlling a Peltier cooler, but again this approach is too complex and bulky for most applications.

Thermocouples are by far the most widespread contact-type temperature transducers in use today.

A better technique (**Fig 2a**) employs an electronic-compensation circuit, which tracks the cold-junction temperature instead of maintaining the junction at a constant temperature. The circuit offers the same result as an ice bath, but is simpler to implement. It produces 0V at 0°C, and its slope of output voltage vs temperature is the same as that of the thermocouple, over the expected range of cold-junction temperatures. For proper operation, the compensator's temperature sensor must be isothermal with the cold junction.

The cold-junction compensator, IC_1, measures the cold-junction's ambient temperature and generates output voltages that are scaled for use with E-, J-, K-, R-, S-, and T-type thermocouples. Low supply current in IC_1 minimizes the self-heating that would otherwise degrade isothermal operation with the cold junction; low power consumption also supports battery operation. The chip's ±0.5% accuracy is compatible with the overall accuracy achievable in a thermocouple-based system.

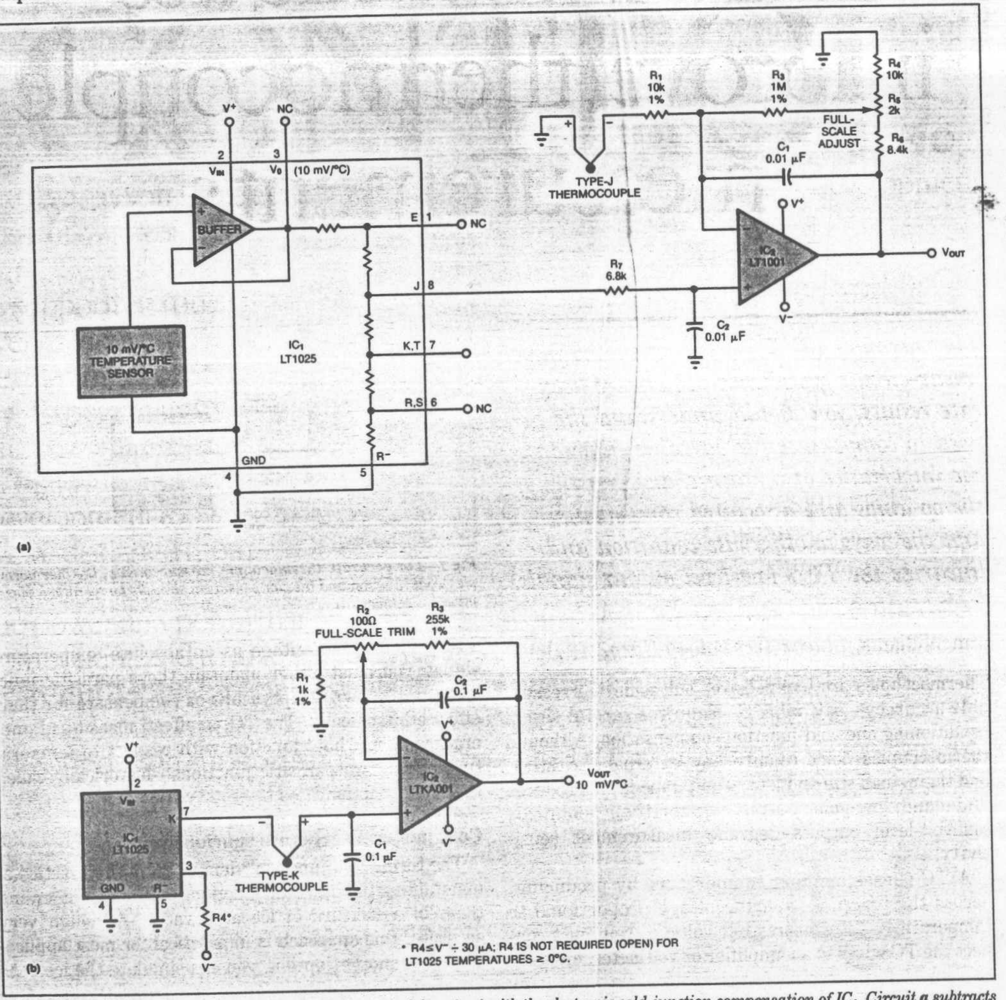


Fig 2—Each of these circuits combines the thermocouple's output *with the electronic cold-junction compensation of IC_1. Circuit **a** subtracts these voltages; circuit **b** arranges the voltages in a series-opposed fashion and amplifies the difference.*

Subzero temperature swings V_{OUT} negative

The op amp in **Fig 2a** amplifies the difference between the thermocouple voltage and the cold-junction-compensation voltage from IC_1. C_1 and C_2 provide filtering, and potentiometer R_5 trims the signal gain. R_6 has a typical value; another value may better accommodate the desired trim range. Reducing R_6 and increasing R_5, for example, will provide higher gain with lower trim resolution. **Fig 2b** shows a similar circuit, for a type-K thermocouple, which combines the TC and compensation voltages in series-opposed fashion. The optional pulldown resistor (R_4) allows V_{OUT} to swing negative, thereby representing sub-0°C temperatures.

Low bias current in IC_2 is important to avoid offset errors due to the op amp's input filter (R_7, C_2) and the output impedance of IC_1. Type-J, -K, -E, and -T thermocouples, which have Seebeck coefficients of 40 to 60 μV/°C, require high-grade precision bipolar amplifiers such as **Fig 2b**'s LTKA001. (This device provides 30-μV offset voltage, 1.5-μV/°C drift, and 1-nA input bias current.)

Particularly critical applications call for a chopper-stabilized amplifier such as **Fig 2b**'s LTC1052 (5-μV offset, 0.05-μV/°C drift, 30-pA input bias current, and 30×10^6 open-loop gain). This amplifier is appropriate for use with type-R and -S thermocouples (whose Seebeck coefficients range from 6 to 15 μV/°C), especially if the application covers a large swing in ambient temperature or does not allow offset adjustments.

Another source of error in thermocouple amplifiers is inadequate open-loop gain. An amplifier for type-K thermocouples, for instance, which produces 100 mV/°C, must have a closed-loop gain of 2500. In this application, an ordinary op amp that specs a minimum open-loop gain of 50×10^3 would produce a $(2500/50{,}000)\times100=5\%$ gain error! Although normally you would calibrate the closed-loop gain by trimming, temperature drift in the open-loop gain can still degrade the output accuracy. The minimum recommended open-loop gain for use with type-E, -J, -K, and -T thermocouples is 250,000. This value is also adequate for use with type-R and -S thermocouples, if the amplifier's output produces 10 mV/°C or less.

Eschew kovar package leads

Regardless of the type of op amp that you choose, a dual-in-line package is preferable to a TO-5 metal can, especially if the op amp's supply current exceeds 500 μA. The TO-5's kovar leads introduce thermocouple effects that can generate ac and dc offsets in the presence of external air motion or thermal gradients in the package.

You should also be aware of considerations related to, but external to the thermocouple amplifier itself. These include overvoltage protection, common-mode voltage, and noise. Protection is necessary because thermocouple wires often pick up static voltages or make contact with high voltage that can damage the amplifier circuit.

The R_{LIMIT} resistor in **Fig 3a,** for instance, attenuates

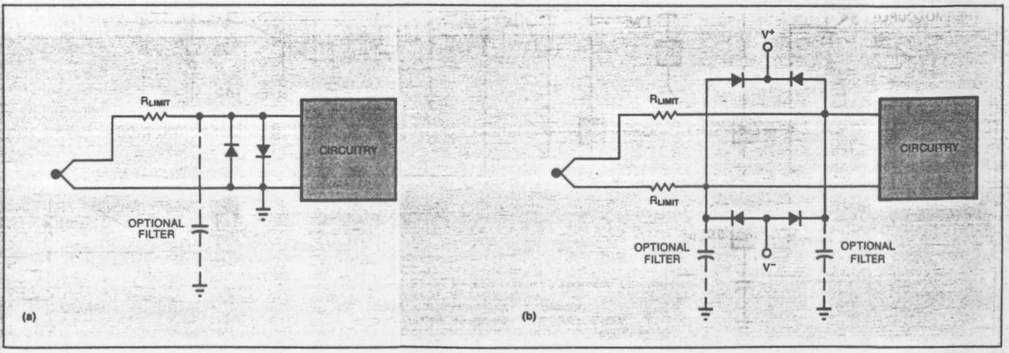


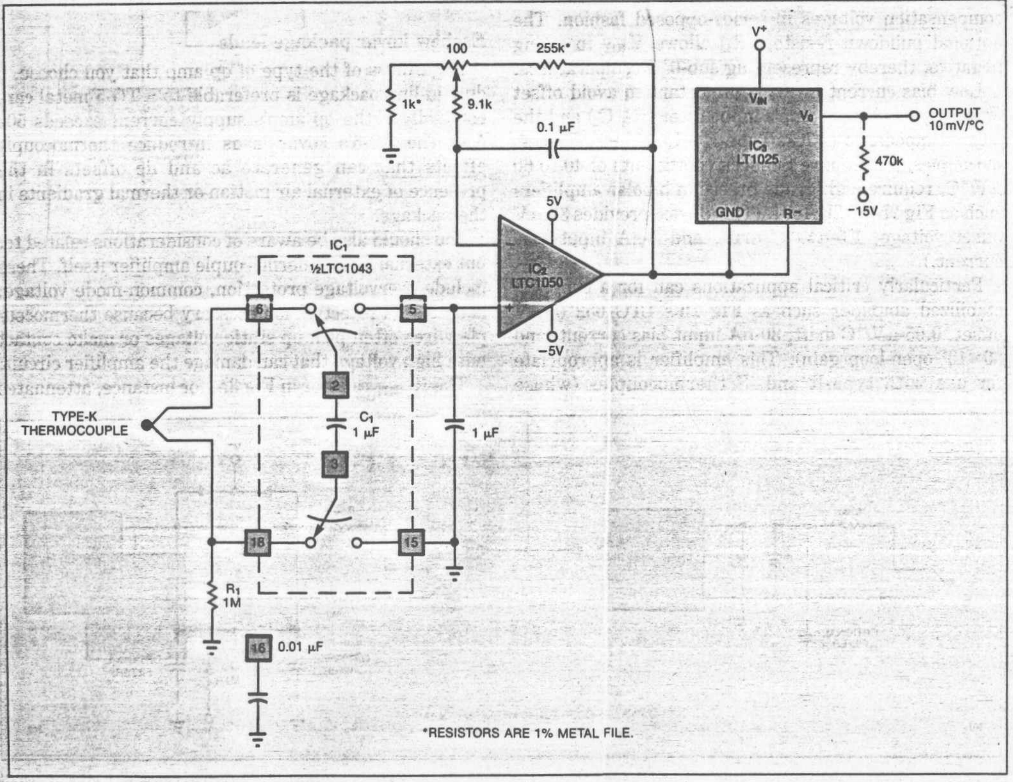
Fig 3—The resistors you see here protect the circuits *from overvoltage on the thermocouple lines. The optional capacitors provide signal filtering for grounded or battery-operated systems (**a**), or for systems (**b**) subject to open ground connections or open thermocouple lines.*

> *Electronic cold-junction compensation tracks the junction temperature instead of maintaining the junction at a constant temperature.*

fault voltages. And, by adding a capacitor (shown as dashed lines), you can obtain signal filtering as well. **Fig 3b's** circuit shows balanced protection for a differential input. Again, connecting the optional capacitors provides lowpass signal filtering in addition to overvoltage protection. The diodes are effective in clamping the signal path to the supply voltages, but you must evaluate the effect of diode-leakage currents, especially if the limit resistors have high values. Similarly, bias currents flowing into the amplifier circuitry through high-value limit resistors can generate measurement errors. In some cases you must compromise accuracy to meet a system's requirements for voltage protection and noise rejection.

The amplifier circuit of **Fig 4** combines filtering with full differential sensing of the thermocouple voltage. If all signals remain within the supply-voltage range of the switched-capacitor building block (IC_1), the circuit provides 120 dB of common-mode rejection. (If the signals exceed this range, the circuit may require protection networks as discussed with regard to **Fig 3.**) Switch action within IC_1 transfers charge from the external "flying capacitor" C_1 to the external output capacitor, C_2. You can vary this rate of transfer, and hence the overall bandwidth, by controlling the chip's commutating frequency. Resistor R_1 provides a bias-current path for IC_1's floating inputs, and the pulldown resistor (shown as dotted lines) enables subzero-temperature readings.

Protection networks and differential operation may not suffice in thermocouple applications that have high levels of noise and common-mode voltage. Industrial environments, for example, can generate ground-potential differences of 100V or more. For these conditions, you must galvanically isolate the thermocouple and its signal-conditioning circuitry from ground. The circuit requires a fully isolated power source and an isolated signal-transmission path that is referred to ground at the output. Careful design allows a single path to transfer both the floating power and the isolated signals. What's more, thermocouples allow you to trade bandwidth for dc accuracy.

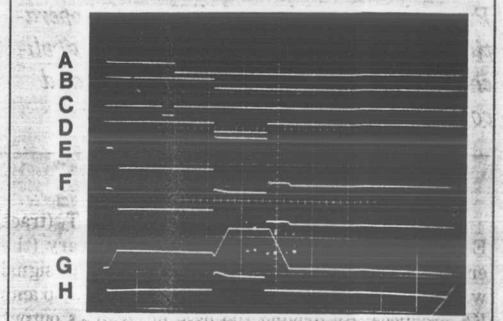


*RESISTORS ARE 1% METAL FILE.

Fig 4—This differential-input thermocouple amplifier implements "flying capacitor" isolation with a switched-capacitor circuit (IC_1).

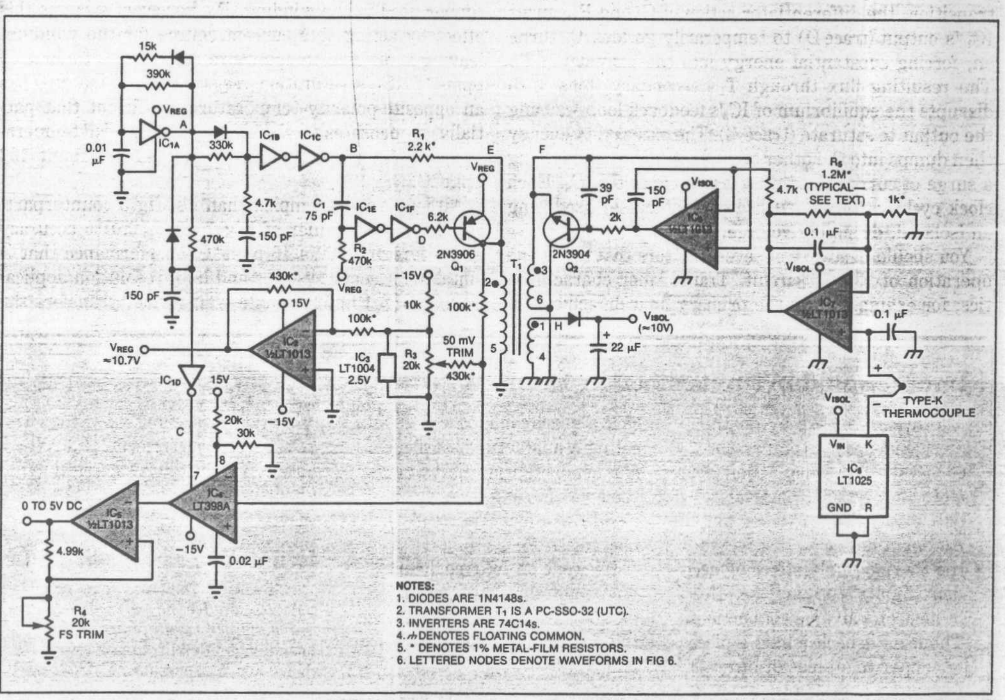
One transformer isolates signal and power

The isolated signal conditioner of **Fig 5** provides ±0.25% accuracy in the presence of 175V common-mode voltages. A single transformer, T_1, transmits the isolated power and data. First of all, take note of the oscillator circuit consisting of inverter IC_{1A} and associated components, which generates the clock signal shown in **Fig 6,** trace A. Inverters IC_{1B}, IC_{1C}, and associated components stretch the positive pulses in this signal (trace B), and apply them to the 2.2-kΩ resistor, R_1. The pulse amplitudes are stable because the inverters obtain a stable supply voltage from the (approximate) 10.7V regulator consisting of IC_2 and IC_3.



TRACE	VERTICAL	HORIZONTAL
A	50V/DIV	50 µSEC/DIV
B	50V/DIV	50 µSEC/DIV
C	50V/DIV	50 µSEC/DIV
D	50V/DIV	50 µSEC/DIV
E	10V/DIV	50 µSEC/DIV
F	10V/DIV	50 µSEC/DIV
G	10V/DIV	50 µSEC/DIV
H	50 mA/DIV	50 µSEC/DIV

***Fig 6—These waveforms depict selected signals from Fig 5's circuit.** The negative-pulse level in trace E, for example, represents the desired thermocouple temperature.*



NOTES:
1. DIODES ARE 1N4148s.
2. TRANSFORMER T_1 IS A PC-SSO-32 (UTC).
3. INVERTERS ARE 74C14s.
4. ⏚ DENOTES FLOATING COMMON.
5. * DENOTES 1% METAL-FILM RESISTORS.
6. LETTERED NODES DENOTE WAVEFORMS IN FIG 6.

***Fig 5—Transformer T_1 provides 175V isolation** for the power and signals of this thermocouple-signal conditioner. Accuracy is ±0.25%.*

Protection networks and differential operation may not suffice in thermocouple applications that have high levels of noise and common-mode voltage.

Current pulses in R_1 drive the primary of T_1 (trace E), producing voltage pulses in the secondary (the emitter of Q_2, trace F). Op amp IC_6 compares this signal with the conditioned thermocouple voltage that op amp IC_7 produces. By driving the base of Q_2, IC_6's output (trace G) forces the transformer's secondary voltage (pin 3) to clamp at the level of IC_7's output. The clamping action is active for low output voltages because Q_2 operates in the inverted mode.

T_1's primary voltage clamps in response to a clamp on the secondary voltage. After IC_6's output settles, the stable, clamped primary voltage represents the thermocouple's output signal. Meanwhile, a delayed clock signal (trace C) from inverter IC_{1D} controls the sample/hold amplifier, IC_4, causing that device to sample the T_1 primary voltage. IC_4 returns to the hold mode when the clock waveform (trace A) goes low. Potentiometer R_3 adjusts the sample/hold signal's offset, and potentiometer R_4 adjusts the gain.

When IC_{1C}'s output (trace B) makes a high-to-low transition, the differentiator action of C_1 and R_2 causes IC_{1F}'s output (trace D) to temporarily go low. Q_1 turns on, forcing substantial energy into the primary of T_1. The resulting flux through T_1's secondary (pins 3, 6) disrupts the equilibrium of IC_6's feedback loop, causing the output to saturate (trace G). The excess flux energy then dumps into the other secondary (pins 1, 4), forcing a surge of current into the storage capacitor, C_3. Each clock cycle generates such a current pulse, producing an isolated, dc supply voltage, V_{ISOL}.

You should be aware of several factors that affect the operation of **Fig 5**'s circuit. Transformer characteristics, for example, form the primary limit on achievable accuracy. The clamping scheme relies on avoiding saturation of the transformer's core. The clamp interval must be short, and T_1's primary current during this interval should remain extremely low with respect to the core-saturation value. The power-refresh pulse occurs immediately after the data transfer rather than before, to allow a pause for the transformer's core to recover from saturation. The low clock frequency (350 Hz) ensures adequate time intervals for this purpose; the resulting low bandwidth is not of consequence in most thermocouple applications.

To trim the circuit's gain, select R_5 (IC_7's feedback resistor) according to the desired maximum temperature and the thermocouple type. You should set IC_7's output to 50 mV before adjusting the offset trim (R_3); the circuit cannot read IC_7 outputs below 20 mV because of saturation in Q_2. The drift of the output voltage vs temperature depends on constant-magnitude current pulses into the primary winding of T_1, which in turn depends on the temperature coefficient of the copper used in the winding. R_1, however, swamps this effect by acting as a current source for the winding, leaving a residual temperature coefficient of about 60 ppm/°C. IC_{1C}'s saturation resistance, fortunately, has an opposite-polarity temperature coefficient that partially compensates for the residue. The overall temperature coefficient, including that of IC_3, is about 100 ppm/°C.

Although more complex than its **Fig 5** counterpart, the isolation amplifier of **Fig 7** offers 0.01% accuracy and a typical drift of 10 ppm/°C—performance that is suitable for servo systems and high-resolution applications. As in **Fig 5**, a single transformer transfers the isolated data and power. The thermocouple voltage, however, undergoes pulse-width modulation before coupling across the transformer. The circuit then demodulates this signal back to dc.

Again, inverter IC_{1A} generates the clock waveform (**Fig 8**, trace A). This waveform's high-to-low transition sets flip-flop IC_2 (trace B), after a small delay introduced by inverters IC_{1B}, IC_{1C}, and associated components. The clock signal, buffered by inverters IC_{1D} and IC_{1E}, also drives the primary of T_1 (trace C). As a result, the T_1 secondary receives energy and delivers it to the storage capacitor, C_1, creating V_{ISOL}, the isolated supply voltage for that side of the circuit.

Besides generating V_{ISOL}, pulses in the T_1 secondary clock the pulse-width modulator, a closed-loop circuit that includes IC_{4B}, IC_{6B}, IC_{7A}, and IC_{7B}. Op amp IC_8 amplifies the thermocouple signal and applies it to the noninverting input of IC_{6B}, which in turn servo-biases comparator IC_{7A}. Each time that IC_{7B} allows C_2 (trace E) to receive charge via resistor R_1, IC_{7A} produces a pulse whose duration is proportional to the thermocouple voltage. After inversion by IC_{2A}, these pulses also drive the R_2/C_3 integrator, which delivers a dc voltage to the inverting input of IC_{6B}. C_6 provides compensation for the feedback loop.

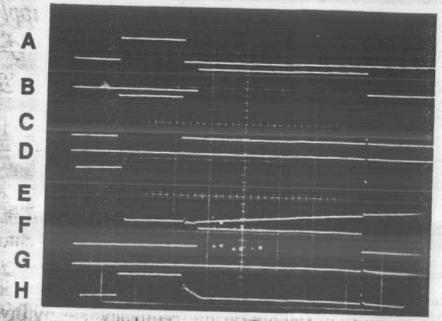
In case you don't remember Dr Seebeck

Thermocouples are by far the most widespread temperature sensors in use today. Their principle of operation, however, dates back to 1822, when an Estonian physician discovered the thermocouple effect by accident. While studying the effects of heat on galvanic connections, Thomas Seebeck joined a piece of copper to a piece of bismuth, forming a loop. He then noted that a nearby compass was indicating a magnetic disturbance. Not realizing that electric current was flowing, Seebeck labeled the effect "thermomagnetism."

He went on to experiment with different combinations of metals and eventually published the results of his work (**Ref 1**). Further investigations, of course, have established that "thermomagnetism," now known as the "Seebeck effect," is a reliable and repeatable electrical phenomenon.

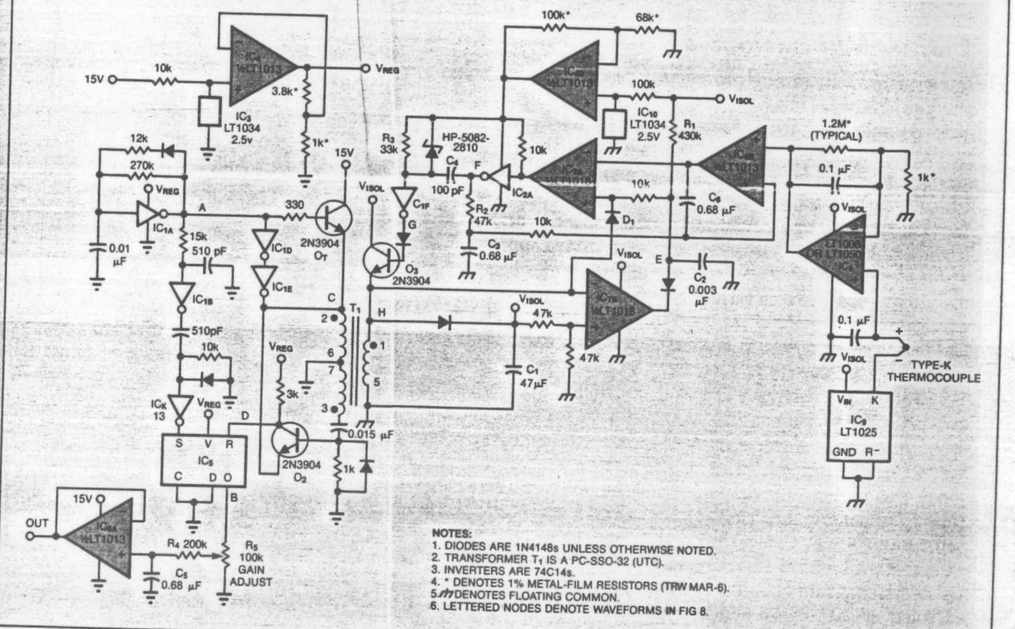
Reference

1. Seebeck, Thomas, *Magnetische polarisation der metalle und erze durch temperatur-differenz*, Abhaandlungen der Preussischen Akademie der Wissenschaften, 1823, pg 265-373.



TRACE	VERTICAL	HORIZONTAL
A	20V/DIV	50 µSEC/DIV
B	20V/DIV	50 µSEC/DIV
C	10V/DIV	50 µSEC/DIV
D	20V/DIV	50 µSEC/DIV
E	2V/DIV	50 µSEC/DIV
F	10V/DIV	50 µSEC/DIV
G	10V/DIV	50 µSEC/DIV
H	20V/DIV	50 µSEC/DIV

***Fig 8—The positive pulse width in trace B of the Fig 7 circuit** corresponds to the thermocouple's temperature.*



NOTES:
1. DIODES ARE 1N4148s UNLESS OTHERWISE NOTED.
2. TRANSFORMER T1 IS A PC-SSO-32 (UTC).
3. INVERTERS ARE 74C14s.
4. * DENOTES 1% METAL-FILM RESISTORS (TRW MAR-6).
5. ⏚ DENOTES FLOATING COMMON.
6. LETTERED NODES DENOTE WAVEFORMS IN FIG 8.

***Fig 7—In this isolation circuit,** pulse-width modulated thermocouple signals are transferred across the transformer barrier. Accuracy is ±0.01%.*

Variations in ambient temperature, supply voltage, and clock frequency have little effect on the PWM isolation amplifier's signal output.

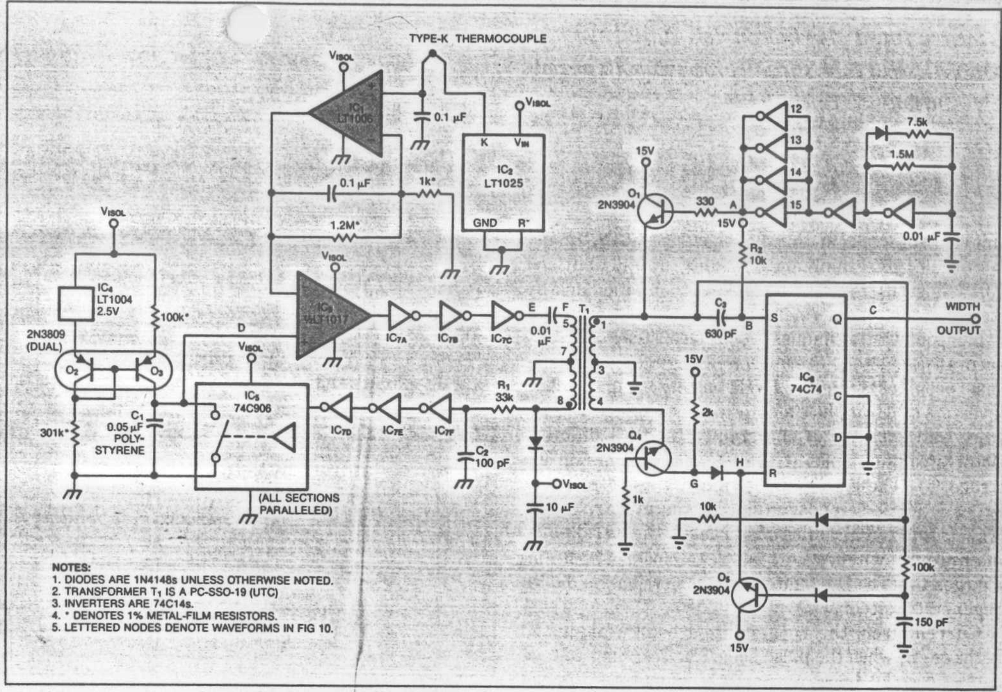
Circuit accuracy demands stable pulse widths at the output of IC$_{2A}$. IC$_{2A}$'s low-loss, MOS switching characteristics contribute to the precise timing necessary, as does the stabilized supply voltage that IC$_{4B}$ provides. The stability of the operating frequency (set by inverter IC$_{1A}$) has little effect on the pulse widths because this frequency is common to the primary-side demodulation scheme.

Demodulation proceeds as follows: C$_4$ and R$_3$ differentiate the negative-going edge of IC$_{2A}$'s output, causing IC$_{1F}$ to deliver a pulse (trace G) to the base of Q$_3$. In response, Q$_3$ delivers a fast spike to T$_1$'s secondary (trace H). (Diode D$_1$ at IC$_{7A}$'s noninverting input breaks a regenerative loop that could cause oscillation.) T$_1$'s primary section between pins 7 and 3 receives the spike, which then drives the base of Q$_2$. Q$_2$ behaves as a clocked demodulator, pulling its collector low (trace D) only when its base is high and its emitter is low—when T$_1$ is transferring data rather than power.

The collector spike from Q$_2$ resets flip-flop IC$_5$. Like IC$_{2A}$, this flip-flop is an MOS device powered by a stable supply (obtained from IC$_4$), and clocked by the same frequency as the pulse-width modulator. As a result, the flip-flop's Q output signal has a dc-average value that depends primarily on the desired thermocouple signal at IC$_8$'s output. Variations in the ambient temperature, supply voltage, and clock frequency have little effect.

Delay translates to offset error

Filter components R$_4$ and C$_5$ extract the signal's dc value; R$_5$ permits adjustment of the overall gain. The voltage follower, IC$_{6A}$, produces the circuit's output. Because this scheme depends on the accurate timing of edge signals at the flip-flop, you must account for the small delay in discharging C$_2$ (trace E) to avoid a small offset error. The delay in IC$_5$'s S (set) line compensates for this error by setting the rising edge of trace B coincident with that of trace F. Trace B's falling edge requires no such compensation because wideband cir-



NOTES:
1. DIODES ARE 1N4148s UNLESS OTHERWISE NOTED.
2. TRANSFORMER T$_1$ IS A PC-SSO-19 (UTC)
3. INVERTERS ARE 74C14s.
4. * DENOTES 1% METAL-FILM RESISTORS.
5. LETTERED NODES DENOTE WAVEFORMS IN FIG 10.

Fig 9—This thermocouple amplifier provides signal conditioning, isolation, and a pulse-width modulated output.

Additional error sources in thermocouple systems

You must exercise care in processing the low-level signals that thermocouples produce. In general, thermocouple *system* accuracies greater than 0.5°C are difficult to achieve. Besides the major sources of error that the accompanying article discusses in detail, you should be aware of the effects that the connection wires, cold-junction uncertainties, and the faulty placement of sensors can have.

The wires that you use to connect a thermocouple and its conditioning circuitry form additional, unwanted thermocouple junctions. You should maintain these junctions at the same temperature to minimize their effect, which you can usually do by mounting them close togther. In some cases, you can eliminate a junction by selecting appropriate connecting wires and other accessories; consult **Ref 1**, for example.

The joining of dissimilar metals always produces a thermocouple junction. Such dissimilar metals include the leads of IC packages (kovar in TO-5 cans, alloy 42 or copper in DIPs), and a variety of other metals found in plating finishes and solders. The net effect of all these thermocouple junctions will be zero if they all have the same temperature, but power dissipation usually causes temperature gradients within an IC package or a pc board. Accordingly, you should use extreme care to ensure an absence of temperature gradients, in the vicinity of the thermocouple terminations, in the cold-junction compensator, and in the thermocouple amplifier.

If you can't eliminate a given temperature gradient, then position the sensitive leads isothermally. In the schematics in the accompanying article, sensitive leads include the LT1025's R$^-$ and output pins, the amplifier-input pins, and leads for the gain-setting resistors. One effect to watch for is the apparent drift in an amplifier's offset voltage during warmup. Such an error can amount to tens of microvolts, especially in TO-5 cans with kovar leads—even if drift measures zero for the chip itself.

Junctions infest IC package

The culprit, of course, is mismatched thermocouple materials within the package, in the path from lead frame to bonding wire to IC metallization to silicon. (Lead frame to bonding wire is the dominant junction.) The effect is proportional to power dissipation, and you can minimize it by choosing ICs that draw low supply current, by operating them at low supply voltages, and by avoiding TO-5 cans. You can accommodate the remaining drift by specifying a 5-minute warmup before calibrating the system or measuring its performance.

The thermocouple's cold junction is another significant source of error. A true cold junction (ice-bath reference) will contribute error according to slight deviations from the desired temperature, but an active-compensator IC makes errors in the process of sensing and tracking the ambient temperature. You must take measures to ensure accurate tracking by maintaining the cold junction and the IC at the same temperature. These measures include the use of high-thermal-capacity blocks and thermal shrouds.

Because a thermocouple measures its own temperature, the placement of the thermocouple can also be a source of error. In fluid systems, for instance, eddy currents or the effects of laminar flow around the thermocouple can cause remarkably large errors. Even a simple surface measurement can be inaccurate because of poor thermal conductivity between the surface and the sensor.

Silicone thermal grease can ease this problem, and you should mate as much of the sensor surface as possible to the measured surface. (Ideally, the thermocouple should lodge tightly in a hole drilled in the surface.)

Keep in mind that thermocouple leads act as heat pipes that provide direct thermal paths to the sensor. This isn't a problem if the surface has a large thermal capacity, but other situations may require some thought. For example, you might thermally mate the lead wires to the surface. Also, coiling the wires within the ambient temperature of interest will minimize their heat-pipe effects. You should be skeptical of results, even for applications that are apparently simple. Experiment with several sensor positions and mounting options, and if the results agree you are probably on the right track.

Reference

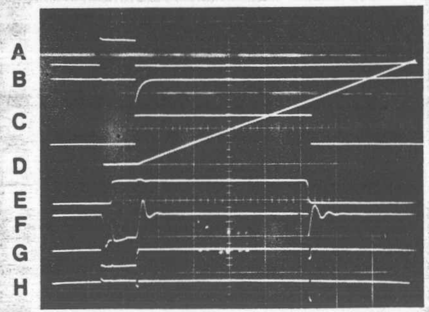
1. *Omega temperature measurement handbook*, Omega Engineering, Stamford, Connecticut, 1987.

Linearizing a thermocouple's signal voltage simplifies further signal processing in many applications.

cuit elements make up that signal path (IC_{1F}, Q_3, T_1, and Q_2). Again, you can obtain 10-ppm/°C overall drift and 0.01% linearity by using the resistors specified and by matching the voltage references, IC_3 and IC_{10}, for drift.

Using similar techniques, you can construct a 0.25%-accurate, isolated, thermocouple-signal conditioner that provides a digital PWM output (**Fig 9**). The inverters of IC_3 produce a buffered clock signal (**Fig 10**, trace A). Q_1 drives T_1. Concurrently, the R_2/C_3 differentiator provides a spike (trace B) that sets flip-flop IC_8 (trace C). The clock pulse applied to T_1's primary appears at the secondary (pin 8), where it drives the V_{ISOL} supply. The pulse also causes the paralleled, open-drain switches within IC_5 to close, which discharges C_1. (The R_1/C_2 filter prevents oscillation due to regenerative feedback.)

Current from the Q_2/Q_3 current source begins to recharge C_1 when the pulse ends. The resulting voltage ramp (trace D) drives one input of comparator IC_5; the signal related to the thermocouple voltage drives the other input. The comparator switches high when these voltages reach equality, causing a pulse to ripple down the IC_{7A}, IC_{7B}, IC_{7C} inverter chain (trace E) and drive T_1's secondary. (Three inverters serve to sharpen the signal's low-to-high transitions.) As a result, T_1's primary produces a negative spike (pin 4) that biases Q_4, causing its collector to go low (trace G).



TRACE	VERTICAL	HORIZONTAL
A	20V/DIV	50 μSEC/DIV
B	20V/DIV	50 μSEC/DIV
C	20V/DIV	50 μSEC/DIV
D	0.05V/DIV	50 μSEC/DIV
E	20V/DIV	50 μSEC/DIV
F	20V/DIV	50 μSEC/DIV
G	50V/DIV	50 μSEC/DIV
H	20V/DIV	50 μSEC/DIV

Fig 10—Of particular interest in these waveforms of the Fig 9 circuit is the pulse-width-modulated output (trace C).

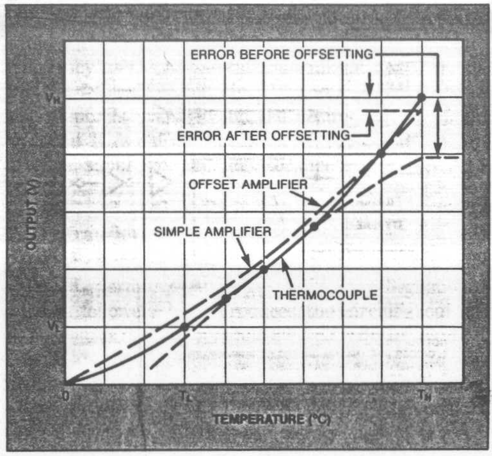


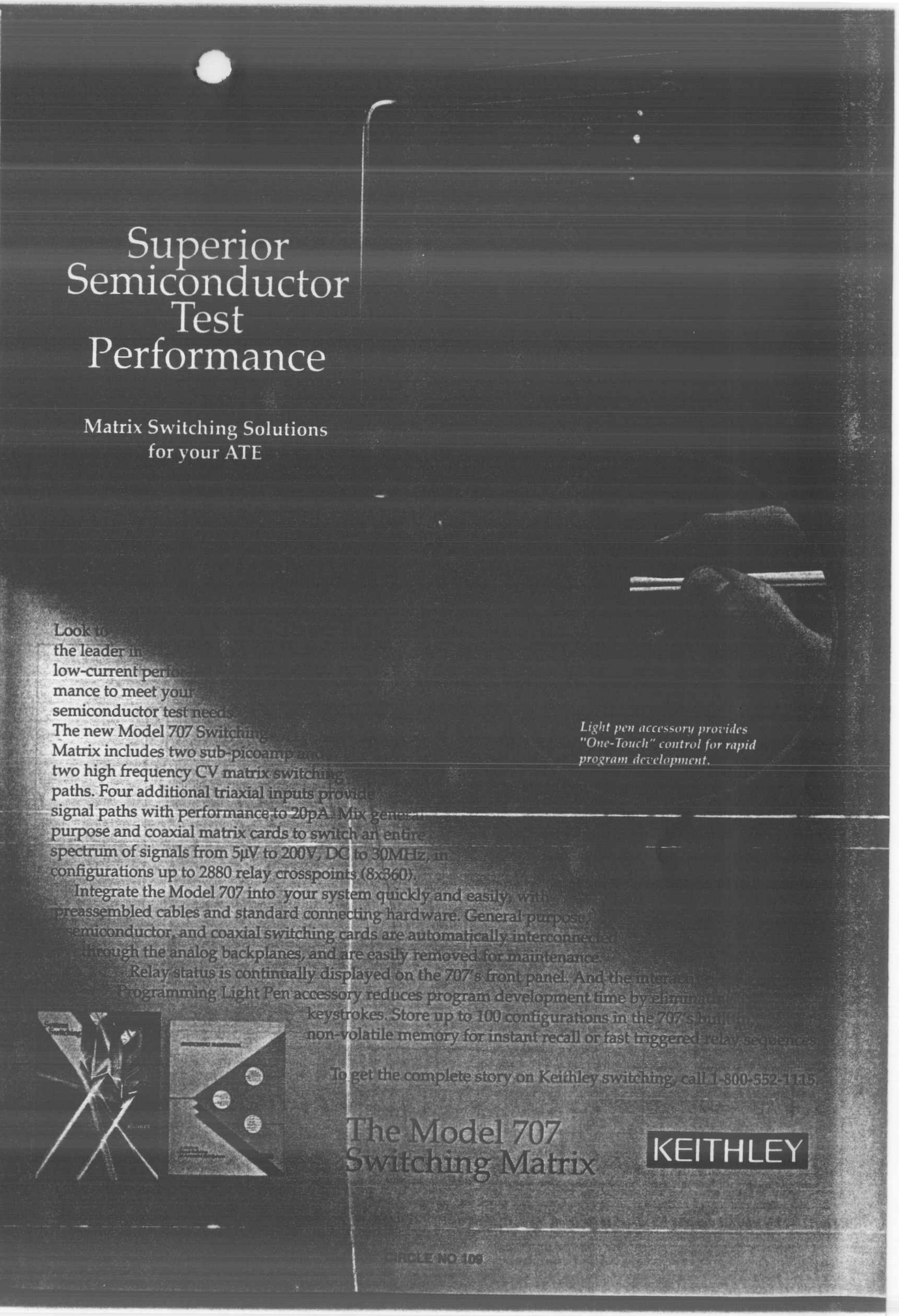
Fig 11—By introducing an offset voltage and shifting the gain of a simple amplifier, *you obtain an output that more closely matches the thermocouple characteristic.*

Transistors Q_4 and Q_5 form a clocked, synchronous demodulator that pulls IC_8's R (reset) pin low only when the clock signal (the emitter of Q_1) is low; this condition occurs during data transfer but not during power transfer. The demodulated output (trace H) contains a single negative spike that resets the flip-flop. Because this spike is synchronous with the high-to-low transition of trace E, IC_8's output-pulse duration (trace C) is proportional to the thermocouple temperature.

Four techniques linearize TC signal

Because a thermocouple's response to temperature is nonlinear, its signal-conditioning circuit produces a nonlinear signal. By linearizing this signal, however, you can simplify further signal processing in many applications. Offset addition, breakpoints, analog computation, and digital correction are four techniques useful for this purpose.

Offset-addition schemes rely on biasing the nonlinear "bow" with a constant term. The resulting output voltage is high at the low end and low at the high end, but errors between these two extremes are reduced (**Fig 11**): The compromise reduces overall error. This approach is suitable for applications in which nonlinearity is either slight over a wide range or great over a narrow range.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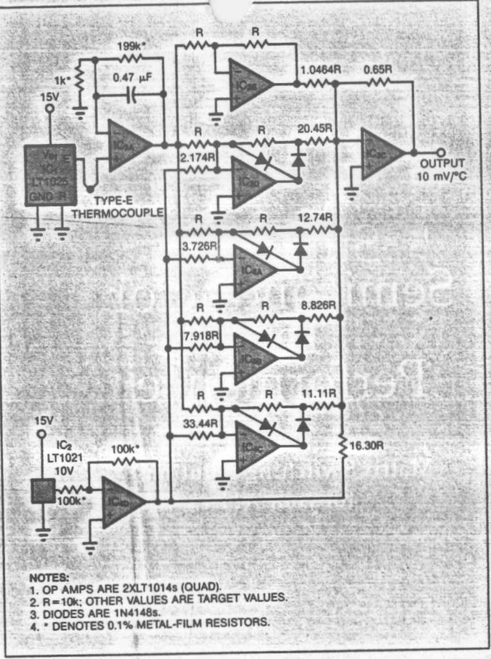
Type-S thermocouples are relatively nonlinear—they generate 6 μV/°C at 25°C and 11 μV/°C at 1000°C. **Fig 12** shows an offset-addition linearizing circuit for such a thermocouple. This circuit is similar to that of Fig 2b, except for the offset term derived from IC_2 and applied through R_4. IC_3 is a chopper-stabilized op amp, useful for minimizing drift. Circuit accuracy is ±3°C for the range of 800 to 1200°C. To calibrate the circuit, set V_T=0.0000V and trim R_5 so that V_{OUT}=1.669V. Then, set V_T=9.585V (T=1000°C) and trim R_2 so that V_{OUT}=9.998V.

The **Fig 13** circuit is an adaptation of a configuration (**Ref 1**) that uses breakpoints to change circuit gain as the input signal varies. This method requires that you scale the input and feedback resistors associated with amplifiers $IC_{4A\text{-}4D}$, IC_{3B}, and IC_{3D}. Current summation at IC_{3C}'s inverting input produces an output voltage that is linear with the thermocouple temperature. Different-value input resistors cause each of the amplifiers, IC_{3D}, IC_{4A}, IC_{4B}, and IC_{4C}, to begin contributing current at a



NOTES:
1. OP AMPS ARE 2XLT1014s (QUAD).
2. R=10k; OTHER VALUES ARE TARGET VALUES.
3. DIODES ARE 1N4148s.
4. * DENOTES 0.1% METAL-FILM RESISTORS.

***Fig 13—The thermocouple's output is linearized** thanks to the introduction of discrete breakpoints (amplifiers IC_{4D}, IC_{4A}, IC_{4B}, and IC_{4C}), which become active at different signal levels.*

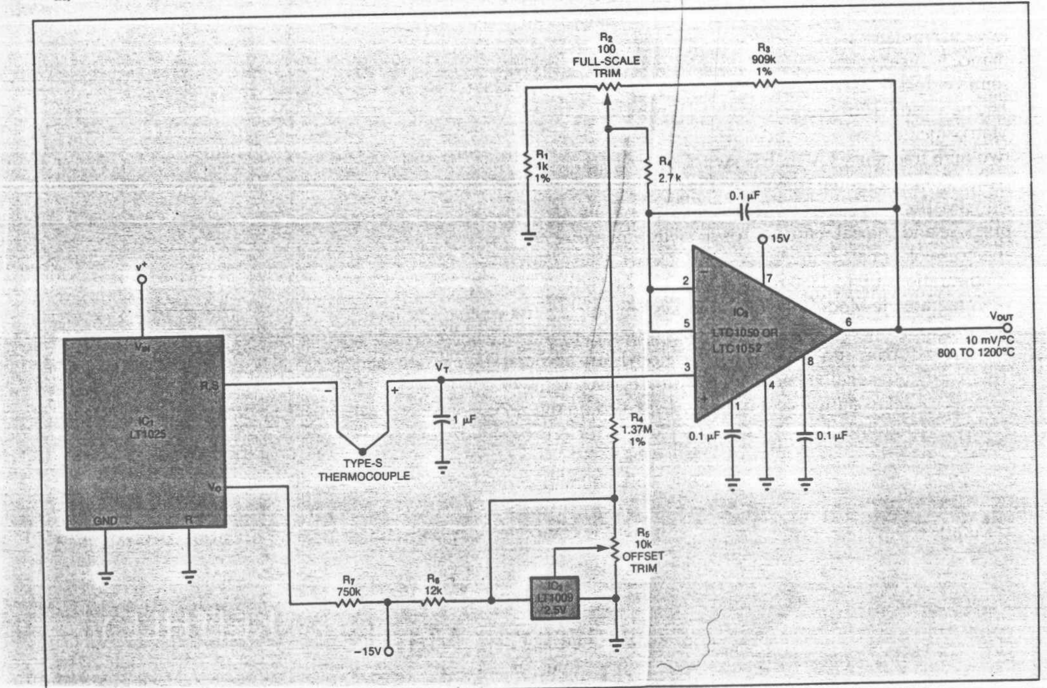


***Fig 12—This circuit derives its offset term** from the 2.5V reference (IC_2) and uses it to help linearize the type-S thermocouple's output.*

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Because they eliminate calibration trimming, digital techniques have become a popular method for linearizing thermocouple signals.

different level of input signal, and the switching diodes produce a piecewise-linear response from each amplifier. For the range of 0 to 650°C, typical circuit accuracy is ±1%.

Fig 14's circuit (Ref 1) replaces the breakpoints with continuous analog-computer functions, uses fewer amplifiers and resistors, and offers similar performance. The multifunction converter, IC_4, linearizes the response by combining a single breakpoint with appropriate scaling.

Implement breakpoints in software

Digital techniques have become popular for linearizing thermocouple signals because they eliminate calibration trimming. For instance, the **Fig 15 circuit**—which Guy M Hoover of Linear Technology Corp developed—feeds a digitized thermocouple voltage to a µP that implements a large number of breakpoints in software. To use the circuit, you simply load the software and apply power; the µP then linearizes the digitized thermocouple signal and stores the result. (*Ed Note: The listing that provides all the necessary code for this application is available by sending a self-addressed, stamped envelope ($0.39 postage) to Software Listings Editor, EDN, 275 Washington St, Newton, MA 02158).*

IC_4 is a 10-bit A/D converter that gives 0.5°C resolution over the 0 to 500°C range. IC_2 amplifies and filters the thermocouple signal; IC_1 provides cold-junction compensation; and IC_3 provides an accurate reference voltage. (To maintain accuracy, the reference requires a minimum 6.5V supply; the A/D converter monitors this voltage via the R_1-R_2 divider.) The 1024-step resolution that IC_4 provides (24 more than the required 1000) ensures 0.5°C of temperature resolution, even for the nonlinear thermocouple characteristic. Linear interpolation between temperature-data points spaced 30°C apart, for example, introduces less than 0.1°C of error.

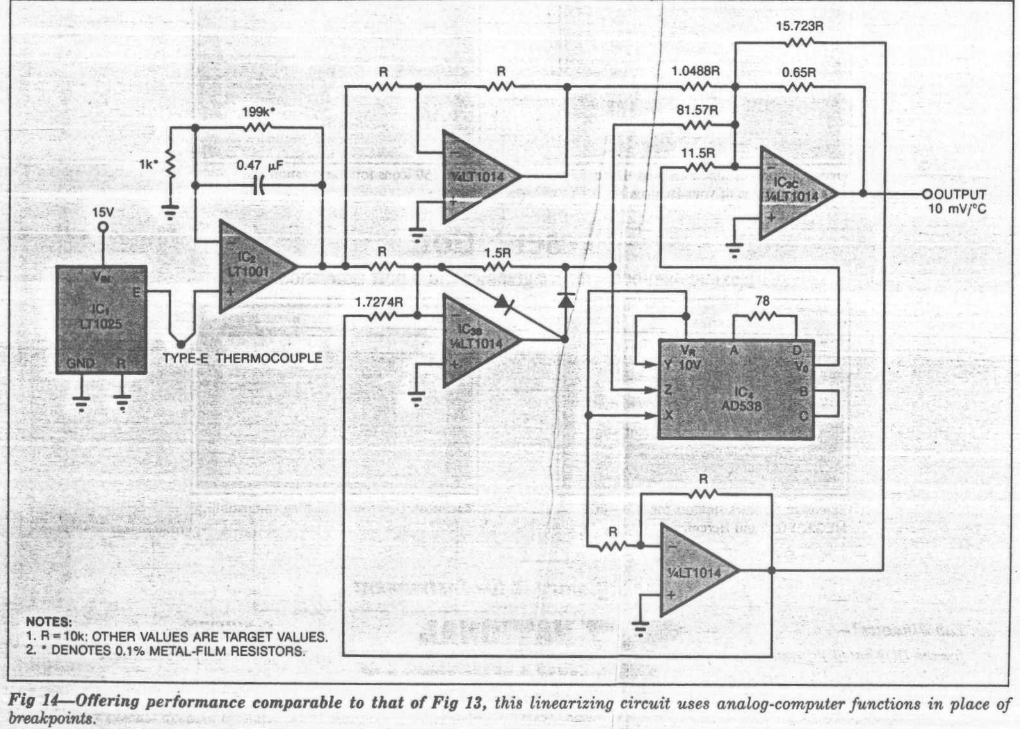
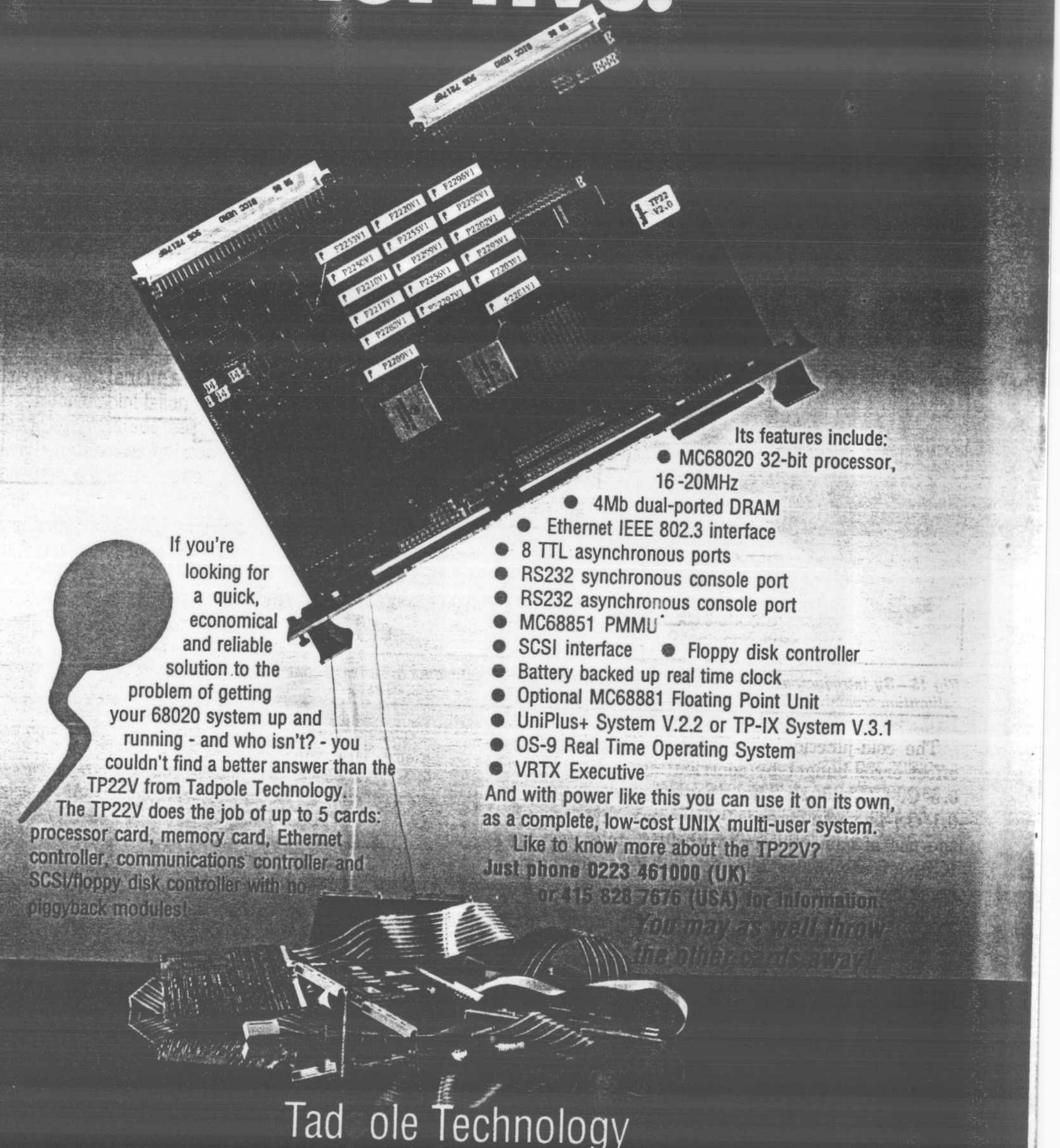


Fig 14—Offering performance comparable to that of Fig 13, this linearizing circuit uses analog-computer functions in place of breakpoints.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CIRCLE NO 108

Eddy currents and the effects of laminar flow around a thermocouple can cause remarkably large measurement errors.

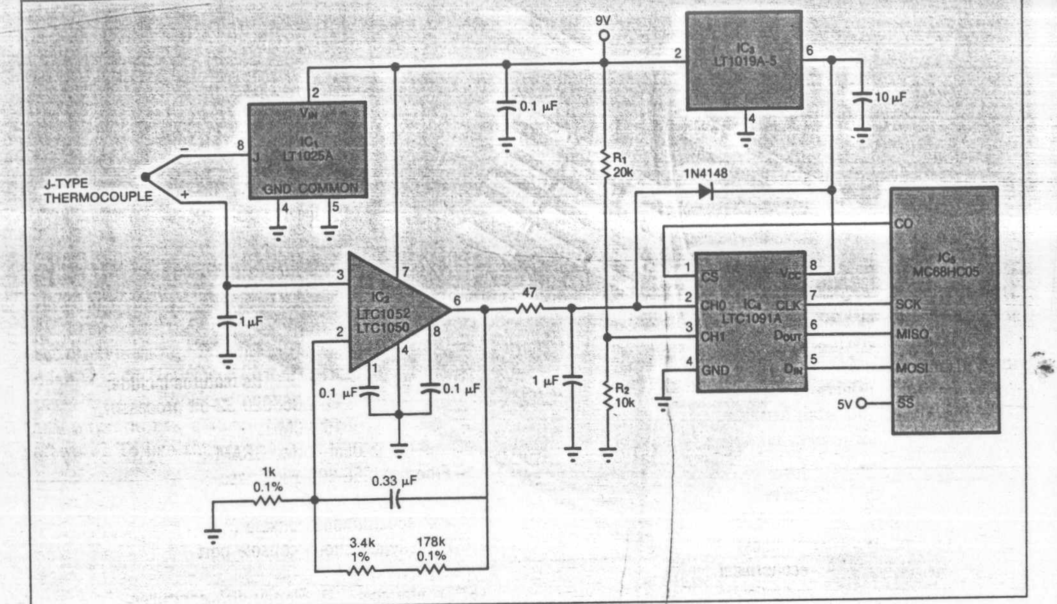

Fig 15—By introducing a microcomputer (IC$_5$) to implement breakpoints in software, this thermocouple-linearizing circuit eliminates calibration trimming. The software listing is available from EDN; see text for details.

The cold-junction compensator, IC$_1$, dominates the offset-error budget by contributing errors as high as 0.5°C. (IC$_4$'s 5-µV offset contributes no more than 0.1°C.) The gain error is 0.75°C max, due primarily to the use of gain resistors with 0.1% tolerance values. IC$_3$'s output-voltage tolerance and IC$_4$'s gain error also contribute to the overall gain error; you can reduce this figure by trimming IC$_3$'s gain resistors. The A/D converter maintains a linearity error below 0.15°C. Typically, these errors combine to produce an overall value of 0.5°C or less, exclusive of the thermocouple itself. Additional wire-connection errors of 0.5 to 1.0°C are not uncommon in practice, but with care you can keep these errors below 0.5°C. **EDN**

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Author's biography

Jim Williams, staff scientist at Linear Technology Corp (Milpitas, CA), specializes in analog-circuit and instrumentation design. He has served in similar capacities at National Semiconductor, Arthur D Little, and the Instrumentation Development Lab at the Massachusetts Institute of Technology. A former student of psychology at Wayne State University, Jim enjoys tennis, art, and collecting antique scientific instruments.

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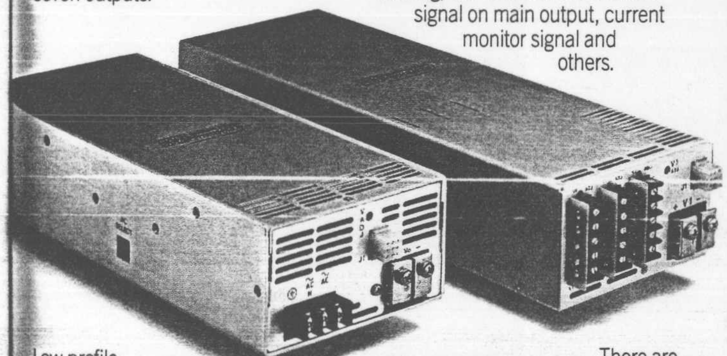

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